BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Path Loss Factors in Lunar Surface Communications - Case 320

DATE: June 28, 1968

FROM: I. I. Rosenblum

ABSTRACT

Factors influencing the signal path loss for lunar surface operations are considered. Current values for lunar surface properties effecting surface propagation (dielectric constant and conductivity) are assigned. Results from calculations of ground wave attenuation, after Vogler, 1964 and antenna height gain, after Norton, 1941 are given in terms of range performance of the Extra-Vehicular Communication System (EVCS), indicating satisfactory operation at 0.5 N.Mile (EVA_1 - EVA_2) and 1.0 N.Mile (EVA_1 - LM).

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MEMORANDUM FOR FILE

I. Introduction

The Apollo Program now includes the possibility of lunar surface exploration by both astronauts simultaneously. Exploration by one astronaut at a time, the other remaining in the LM, is of course still possible.

The dual EVA operational requirements for lunar surface communication are (Reference 1):

0.5 Nautical Mile EVA_1 - EVA_2

1.0 Nautical Mile EVA - LM

Figure 1 illustrates the dual system operation. To implement the communication requirement, MSC has contracted with RCA, Camden, New Jersey to deliver dual Extra-Vehicular Communication System (EVCS) hardware providing three modes of operation: Primary, Secondary and Dual. These modes and associated link frequencies are shown in Figure 2 (from Reference 2) EVA_1 to EVA_2 communication is established via vertical whip antennas mounted on the astronauts' back packs. The EVA to LM link is between the back pack mounted antenna of the EVA and a sleeve dipole antenna mounted near the top of the LM vehicle.

The design specifications for the dual EVCS equipment (Reference 3) allow RCA to assume in their link calculations the following "path losses":

EVA_2 - EVA_1	128db
EVA_1 - LM	119db

Since path loss is a major factor affecting system performance, this study attempts to determine whether the assumed path loss figures can be supported.

II. Path Loss Factors

In order to quantitatively assess path loss, it is necessary to identify those factors which should be included and to leave out those accounted for elsewhere.

The factors listed below are considered in this study in evaluating the "path loss":

- Antenna Gains or Losses (Pattern)
- Antenna Ground Proximity Loss
- Polarization Loss
- Free Space (Inverse Distance Field) Loss
- Ground Wave Attenuation
- Atmospheric (Ionospheric) Loss
- Multipath Loss
- Antenna Height Gain
- Obstacle Loss

A. Antenna Gain

The EVCS antennas are vertical whips extending from the astronaut back packs. The nominal antenna impedance is 50 ohms. The assumption is made that they are $\lambda/4$ or less in length, namely about 10 inches long. The gain of such whip antennas, with proper counterpoise, is approximately 1 relative to isotropic antennas.

The LM antenna is a sleeve dipole antenna located at the top of the LM vehicle, about 25 feet from the base (See Figure 1). The gain of this antenna, like the EVCS one, is low.

As a simplification in this analysis, it will be assumed that both the EVCS and LM antennas are characterized by zero (0) gain antennas. Measured pattern data could, of course, be used as a refinement.

B. Antenna Ground Proximity Loss

An antenna power loss arises when the antenna element is insufficiently removed from the proximity of the ground. This loss can be a significant factor for poorly conducting soils and where ground screens are impractical. Vogler (Reference 4) has evaluated this loss for the lunar surface as a function of antenna height and frequency. Using Vogler's data and making the assumption that the EVA antenna is always at least 1/2 meter above the ground, it is found that this factor can be neglected. This is evident in Figure 3, taken from the Vogler report (See A>5 Curve).

C. Polarization Loss

A polarization loss accrues if the EVCS antenna axis is not oriented in the same plane of polarization as the antenna with which it is working. A non-level position of LM and/or non-vertical position of the EVCS antennas will give rise to this polarization loss. The magnitude of the power loss for dipoles whose planes of polarization differ by an angle γ is given by the factor $\cos^2\gamma$ (Reference 5).

An extreme case would be one in which two antennas are simultaneously off vertical polarization by 18° each in opposite directions. For this case the link loss factor is 0.66 or 1.8 db.

D. Free Space Loss

The free space loss is that signal loss associated with diminishing field strength as an inverse function of the squared distance from the signal source.

The free space loss is calculated in db using the equation:

$$L_{fs} = 32.5 + 20 \log d_o \text{ (km)} + 20 \log f \text{ (MHz)}$$

A plot of the free space loss, L_{fs}, versus distance, d_o, is given in Figure 4 for a frequency, f, of 280 MHz.

E. Ground Wave Attenuation

Ground wave attenuation, A_t, is that loss which takes into account the effects of the terrain between the transmitter and receiver on the propagation of the surface wave r-f field. It is generally a strong function of wave polarization and surface material conductivity and dielectric constant. The zero (0) db reference for the calculation of ground or surface wave attenuation is the free space field intensity.

K. A. Norton in a classic analysis of electromagnetic wave propagation (Reference 6) has given a method for computing field strength, including the effects of ground wave attenuation on the surface wave, using as a model a finitely conducting spherical earth. Norton indicates that by neglecting the higher order terms in his equation (48), the attenuation factor for the surface wave over a plane earth (assumption valid for short distances) can be expressed simply as:

$$A_t = \frac{1}{2p}$$

where p is the "numerical distance" parameter, defined by:

$$p = \pi \frac{r_2}{\lambda} \frac{\mathrm{Cos}^2 b''}{X \, \mathrm{Cos}\, b'}$$

where r_2 = distance

$$b'' = \mathrm{Tan}^{-1} \frac{\varepsilon}{X}$$

$$b' = \mathrm{Tan}^{-1} \frac{\varepsilon - 1}{X}$$

$$X = \frac{1.8 \cdot 10^{15} \, \sigma \, (\mathrm{e.m.u.})}{f \, \mathrm{mc}}$$

λ = wavelength

σ(e.m.u.) = ground conductivity expressed in electromagnetic units

f mc = frequency in megacycles

ε = dielectric constant of the ground referred to air as unity

Norton's method, it appears, could be used to obtain a valid estimate of A_t.

A second method of approximating the ground wave attenuation is by reference to BTL propagation curve data, contained in Reference 7. This excellent data, while calculated for the smooth spherical earth of 4/3 true earth radius, is of questionable adequacy in defining lunar surface wave attenuation of interest here since the calculation did not cover the range of distances desired, nor did it cover propagation over soil of extremely low dielectric constant and conductivity. (Lowest values treated were $\varepsilon = 4$, σe.m.u. = 10^{-14}).

The method chosen to find ground wave attenuation, (A_t), in this study is that given by Vogler in Reference 4, in a study specifically directed at lunar surface propagation. The calculation of A_t using the parametric curves and calculations per Vogler is discussed in more detail in Section IV.

F. Atmospheric (Ionospheric) Loss

B. Elsmore, from a study of observations of CRAB NEBULA during lunar occultation, hypothesized a weak lunar atmosphere with electron concentrations, n, at the surface of 10^3 to 10^4 electron/cm^3 (Reference 4).

Attenuation to wave propagation of such a plasma is a function of the relationship of the signal frequency to the plasma critical frequency.

The critical frequency, in megacycles per second, is given by the following:

$$fcr^2 \approx 8.1 \times 10^{-5} n,$$

where n is the electron concentration.

Thus, the critical frequency of the plasma is less than 1 mc; attenuation at the operating frequencies 259.7 mc; 279.0 mc and 296.8 mc, which are well above fcr, can be altogether neglected.

G. Multipath

Multipath effects can, under certain conditions, result in signal cancellations at the location of the receiver, observable as nulls in the received signal strength. Evaluation of this effect requires detailed knowledge of the antenna heights, information on the electrical properties of the terrain and specific characteristics of the geometrical configuration of the terrain lying between the transmitter and receiver.

A fundamental facet of the analysis undertaken here is the conservative assumption made that precludes the requirement to compute multipath; to wit, it is assumed that the direct wave and ground-reflected wave completely cancel each other out and that as a result, the only signal of consequence at the receiver is the surface wave.*

The lunar surface propagation situation supports the above-mentioned assumption of a reflection coefficient, R, approaching unity. At maximum range, the grazing angle, Ψ, will be about .3° and .6° for the EVA_1 - EVA_2 and EVA_1 - LM paths respectively. The corresponding theoretical reflection coefficient, R, for vertical polarization, low dielectric constant soil, and frequency near 300 MHz, is about .98 and .96 (Ref. 5)

Figure 5 illustrates the multipath geometry.

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*Interest here centers on the maximum range regions and the minimum signal problem. At close-in ranges and somewhat larger grazing angles, multipath effects could possibly give rise to excess (receiver overloading) signal.

Grumman Aircraft Engineering Corporation, (GAEC) in interface control documents (ICD) covering the EVA/LM communications circuit margins, references 8 and 9, calculated reflection losses of 27 db and 21 db respectively for the 0.5 nautical mile and 1.0 nautical mile ranges of the 2 links, corresponding to the ranges and ψ values given above. The extent to which the assumption of complete reflection is conservative can be seen by comparing these values of attenuation with the alternative loss parameter, ground wave attenuation, which as will be seen (Section IV) is approximately 56 db and 61 db respectively.

It is of interest to note that Vogler, (1964), Reference 4, chose not to include the effects of rough terrain or multipath in his rather detailed study of lunar surface radio communication.

A loss of zero (0) db is therefore assigned to the multipath factor.

H. Antenna Height Gain

As the EVCS antennas, or LM antenna, becomes elevated above ground level, an effective height gain is obtained by each antenna. The receiving antenna, for example, at an elevated height will intercept signal energy at a greater field intensity than at ground level; the increase is a height gain. Because of the applicable reciprocity, the transmitting antenna will experience a similar gain at elevated heights.

Curve data from the Bell Telephone Laboratories report 966-6C (Reference 7) permits an estimation of this factor at the frequency of interest and at the assumed antenna elevations. Extrapolations of data for vertical polarization and poor soil conditions yields the following approximate antenna height gains for elevated antennas (See Figure 6):

$EVCS_1$ - 4 ft.	---	10 db
$EVCS_2$ - 4 ft.	---	10 db
LM - 25 ft.	---	24 db

A more detailed and explicit method available for determining antenna height gain is given by K. A. Norton (Reference 6). In Norton's method the height gain of each antenna is given by the expression:

$$f(q) = \left[1 + q^2 - 2q \cos \left(\frac{\pi}{2} + \frac{b}{2}\right) \right]^{1/2}$$

where q and b are determined as a function of height, frequency, and surface material dielectric constant and couductivity, as follows:

$$q = 2\pi \frac{h}{\lambda} \left[\frac{\cos^2 b''}{X \cos b'} \right]^{1/2}$$

$$b'' = \tan^{-1} \left(\frac{\varepsilon r}{x} \right)$$

$$b' = \tan^{-1} \left(\frac{\varepsilon r - 1}{x} \right)$$

$$x = \frac{1.8 \times 10^{15} \ \sigma \ (\text{e.m.u.})}{f \ \text{mc}}$$

Using Norton's method antenna height gains have been determined as follows:

$EVCS_1$	---	4 ft.	---	12 db
$EVCS_2$	---	4 ft.	---	12 db
LM	---	25 ft.	---	28 db

I. Obstacle Loss

During exploration of the lunar surface, the path between EVA's or between EVA and LM may temporarily include a hill or protuberance of arbitrary height. Published BTL and Standard Handbook data permits the estimation of the shadow loss created by such obstacles in the communication path. This loss (approximation) is plotted in Figure 7 as a function of obstacle height, based on data in reference 7.

The general lunar exploration activity is expected to be confined to areas in which visual sight of LM and EVA's to one another will be probable at all times. Under these conditions no obstacles of significant height should be assumed. Accordingly a loss of zero (0) db is assigned to this factor.

III. Electrical Properties of the Lunar Surface Material

The determination of path loss is dependent on the use of estimated values for two key electrical characteristics of the lunar surface, namely dielectric constant and conductivity.

In 1960 Senior and Seigal, through the use of radar data, estimated the relative dielectric constant and conductivity of lunar surface material to be $\varepsilon = 1.1$ and $\sigma = 3.4 \times 10^{-4}$ mhos/m. (Reference 4) Other estimates are now available.

T. Hagfors (Reference 10), of MIT concludes from an examination of recent radar data at $\lambda = 68$ cm, that a dielectric constant of 2.6 would be derived for an assumed homogeneous surface. This figure is in very close agreement with the 2.5 value used in 1968 by Beckman, Reference 8, to explain depolarization of electromagnetic waves back scattered from the lunar surface.

Ness, et.al., Reference 9, from results of magnetic field experiments on lunar Explorer 35 in 1967, concluded that the effective electrical conductivity had a maximum value of 10^{-5} mho/meter.

The two values selected for use in this analysis are

$$\varepsilon = 2.6$$

$$\sigma = 10^{-5} \text{ mho/m} = 10^{-16} \text{ e.m.u.}$$

For comparison it is of interest to note that the 1965 NASA Headquarters - Advanced Missions Division values for electromagnetic constants of lunar material are:

$$\varepsilon = 2.7$$

$$\sigma = 10^{-6} \text{ mho/m}$$

and that Grumman in their interface control documents of 1966 used the values

$$\varepsilon = 2.5$$

$$\sigma = 10^{-4} \text{ mho/m}$$

IV. Ground Wave Attenuation

The method chosen in this study for evaluation of ground wave attenuation, A_t, is after Vogler (Reference 4). Vogler's analysis NBS nomograph 85, "A Study of Lunar Surface Radio Communication", is chosen because it covers the range of surface characteristics of interest (dielectric constant and conductivity) and because the model inlcudes a sphere of lunar radius (r_o = 1738 km).

Vogler's method determines A_t as a function of three parameters, K, b° and X'°, with homogeneous (non-layered) scil, vertical polarization and zero (0) antenna heights assumed at the outset. These parameters are defined as follows:

$$K = \left[\left(\frac{2\pi r_o}{\lambda}\right)^{1/3} |T| \right]^{-1}$$

where

$$T = \left[\sqrt{(\varepsilon_r - 1)^2 + S^2 / (\varepsilon_r^2 + S^2)} \right]^{1/2}$$

$$b^\circ = 2 \tan^{-1} \left(\frac{\varepsilon r}{S}\right) - \tan^{-1} \left(\frac{\varepsilon r - 1}{S}\right)$$

where

$$S = \frac{1.8 \times 10^4 \, \sigma \text{ (mhos/M)}}{f \text{ mc}}$$

$$X_o' = d_o \times f \text{ mc}$$

where r_o = lunar radius

ε_r = surface dielectric constant

σ = conductivity

d_o = distance

Through calculation of the above parameters and the application of data in curve form available in the nomograph, the ground wave attenuation factor can be found directly. (See Figures 8,9 and 10 reproduced from Reference 4)

Calculated values for a range of dielectric constant values and distances of interest are given in Table I.

V. Total Path Loss

The total path loss for the EVA_1 - EVA_2 and EVA_1 - LM links is found by combining the losses and gains associated with the applicable link factors.

The tabulation of path loss for the required operational ranges of the two links is given in Table II. As seen the values cited in the MSC specification to RCA, i.e. path losses of 128 db and 119 db, respectively for the EVA_1 - EVA_2 and EVA_1 - LM links, are supportable.

For convenience, a plot of total path loss vs distance is given for the EVA_2 link in Figure 11. As seen, the zero (0) margin point is reached at a distance of 1.1 n. miles (2.0 Km).

I. I. Rosenblum

I. I. Rosenblum

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Attachments
Tables 1&2
Figures 1-11

REFERENCES

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2. Report of Preliminary Design Review - January 9-10, 1968, Extravehicular Communication System, RCA SDDR-SY-1, January 22, 1968

3. Exhibit A "System Specification for the Extravehicular Communication System (EVCS)", September 30, 1967 - MSC - IESD

4. "A Study of Lunar Surface Radio Communication", L. E. Vogler, 1964

5. Ultra High Frequency Propagation - Reed and Russell - Boston Tech. Publishers Inc., 1964

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7. NDRC Div. 15, Propagation Curves, Issue 3 Report 966-6C, October 1944, BTL U. S. Department of Commerce No. PB-14326

8. "EVA/EVA VHF AM Communications Circuit Margin ICD", GAEC Interface Control Document (ICD) LIS 380-15009, January 31, 1966

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10. "Review of Radar Observations of the Moon", Chapter 12 by T. Hagfors in The Nature of The Lunar Surface - Proceedings of 1965 IAU-NASA Synposium J.H.U. Press

11. "Depolarization of EM Waves Backscattered From The Lunar Surface" - P. Beckmann - J. Of G. R. Vol. 73, No. 2, January 15, 1968

12. "Early Results From The Magnetic Field Experiments on Lunar Explorer 35" - N. F. Ness et.al., J. of G. R., Vol. 72, No. 23, December 1, 1967

TABLE I

GROUND WAVE ATTENUATION

Vertical Polarization
Zero Antenna Heights
$\sigma = 10^{-5}$ Mhos/M
f = 300 MHz

DISTANCE	$\varepsilon = 1.1$	1.2	1.4	2.0	2.6	3.0
10 km	75	79	81	81	81	81
5	65	68	71	71	71	71
2	57	60	62	62	62	62
1	50	55	56	56	56	56
.5	44	47	50	50	50	50
.25	38	42	44	44	44	44
.15	34	38	40	40	40	40

TABLE 2

TABULATION OF PATH LOSS VALUES

		EVA-EVA .5 N.Mile	EVA-LM 1.0 N.Mile
A.	Antenna Gain Gt	0 db	0 db
B.	Antenna Gain Gr	0	0
C.	Antenna Ground Proximity Loss	0	0
D.	Polarization Loss	- 1.8	- 1.8
E.	Free Space Loss	-81.5	-87.5
F.	Ground Wave Attenuation (ε = 2.6)	- 56	- 62
G.	Plasma Loss	0	0
H.	Multipath Loss	0	0
I.	Antenna Height Gain ($h_1 + h_2$)	+ 24 db	+ 40 db
J.	Obstacle Loss	0	0
	TOTAL PATH LOSS	-115.3	-111.3
	EVCS Spec. Values	-128	-119

(f = 300 MHz)

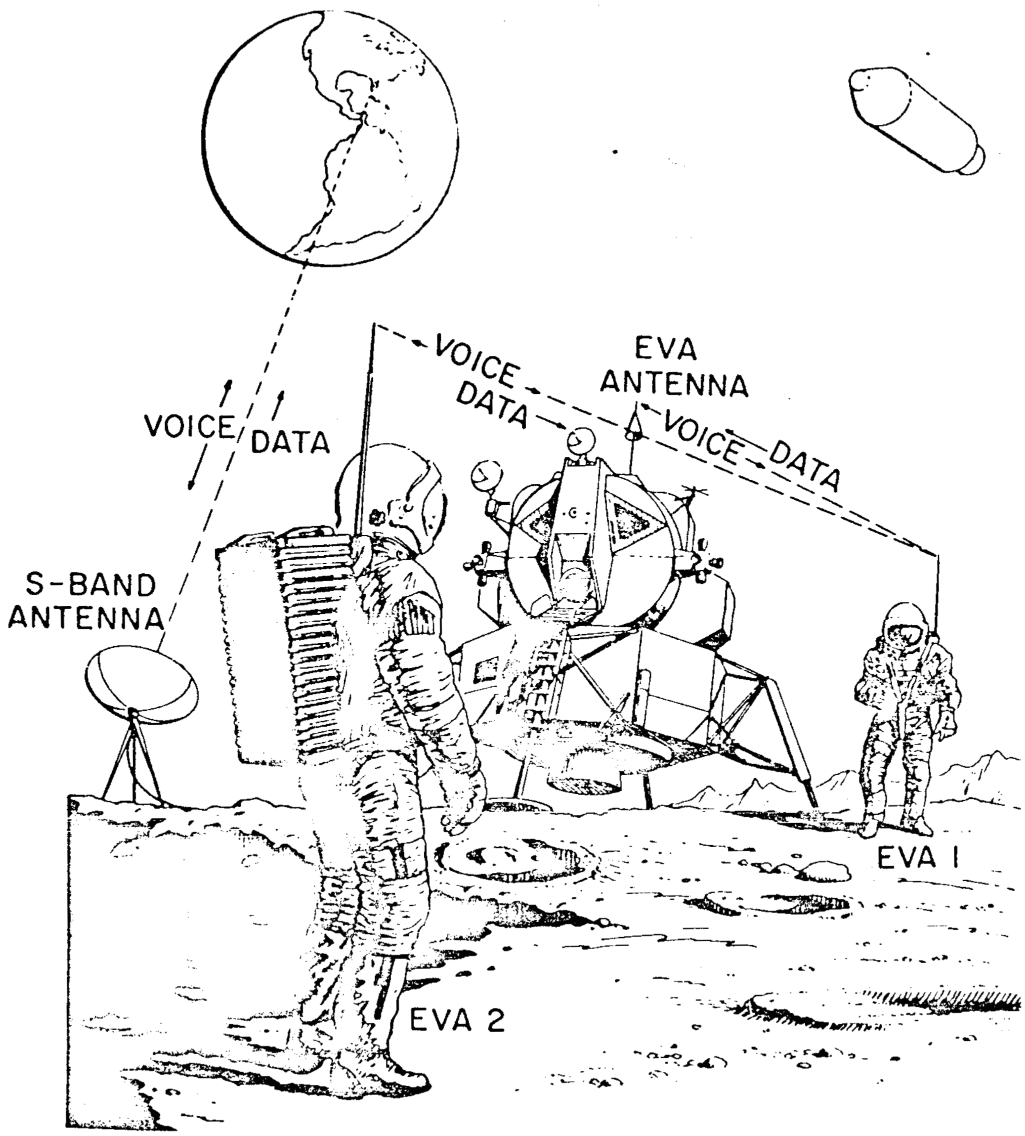


FIGURE 1 - EVCS DUAL MODE OPERATIONS

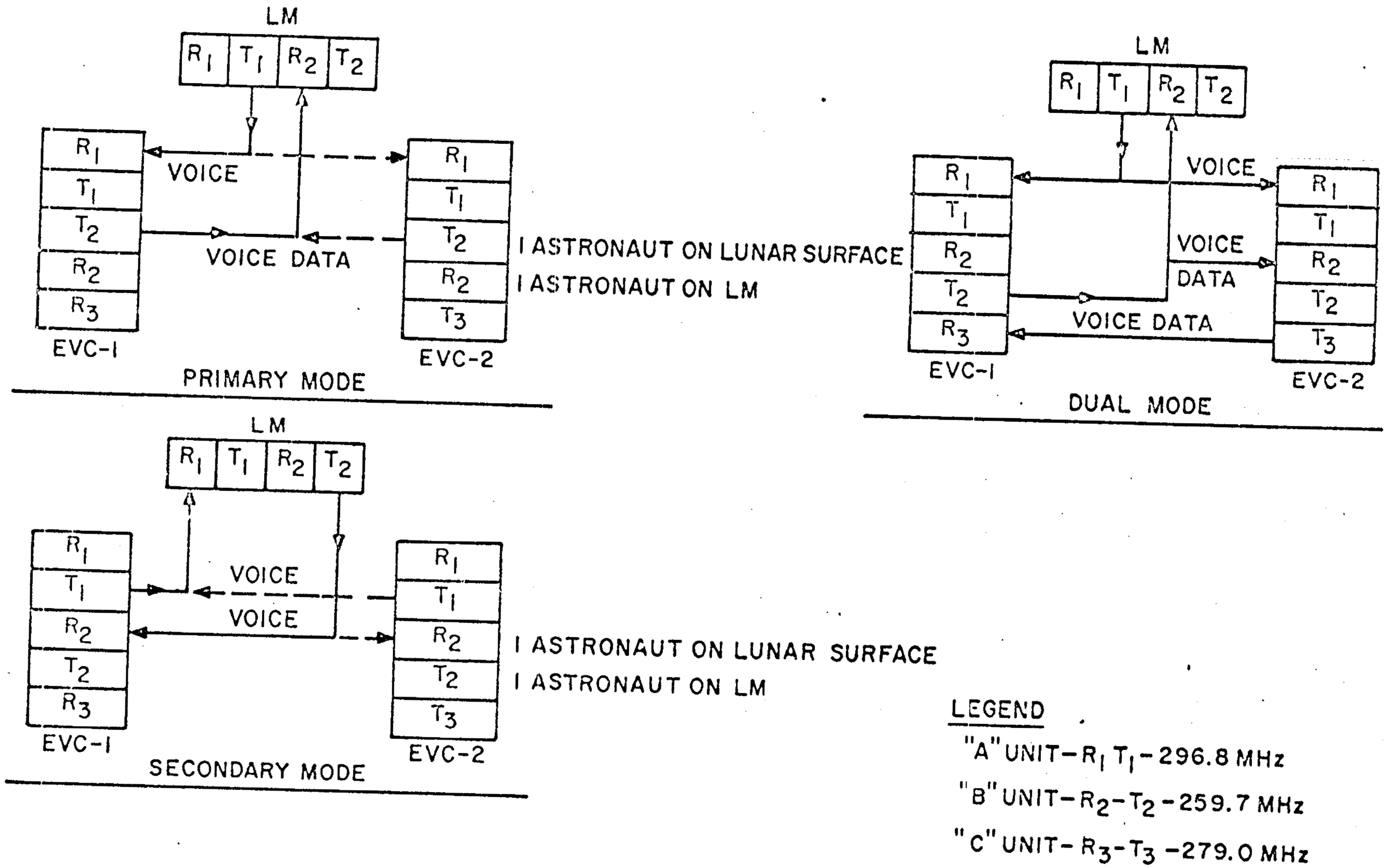
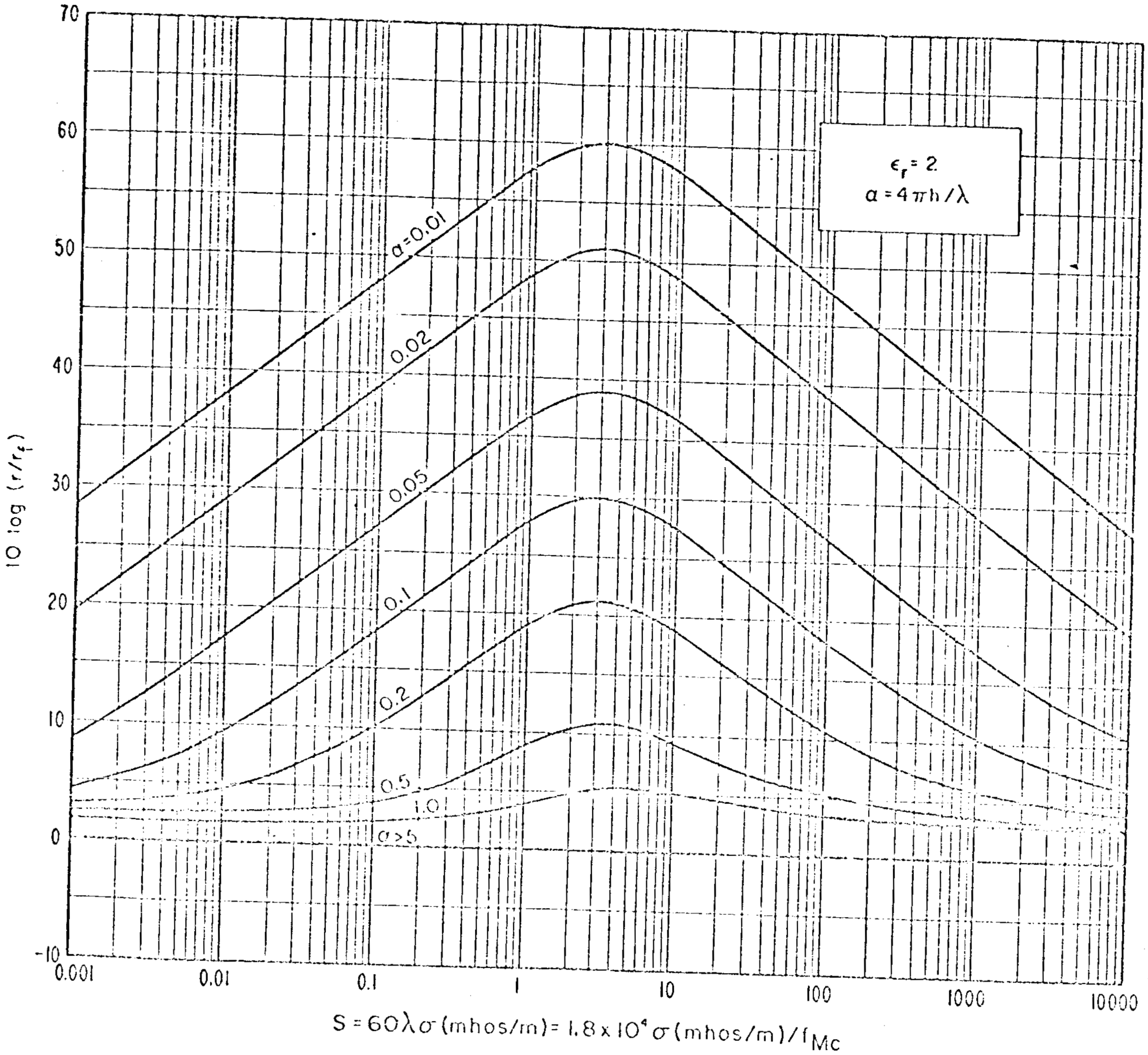


FIGURE 2 - EVCS DUAL MODE OPERATIONS (From ref. 2)



1. 1.

FIGURE 3 . Ground proximity loss $L_{t,r}$ for VED, $\epsilon_r = 2$. (From Vogler - ref. 4)

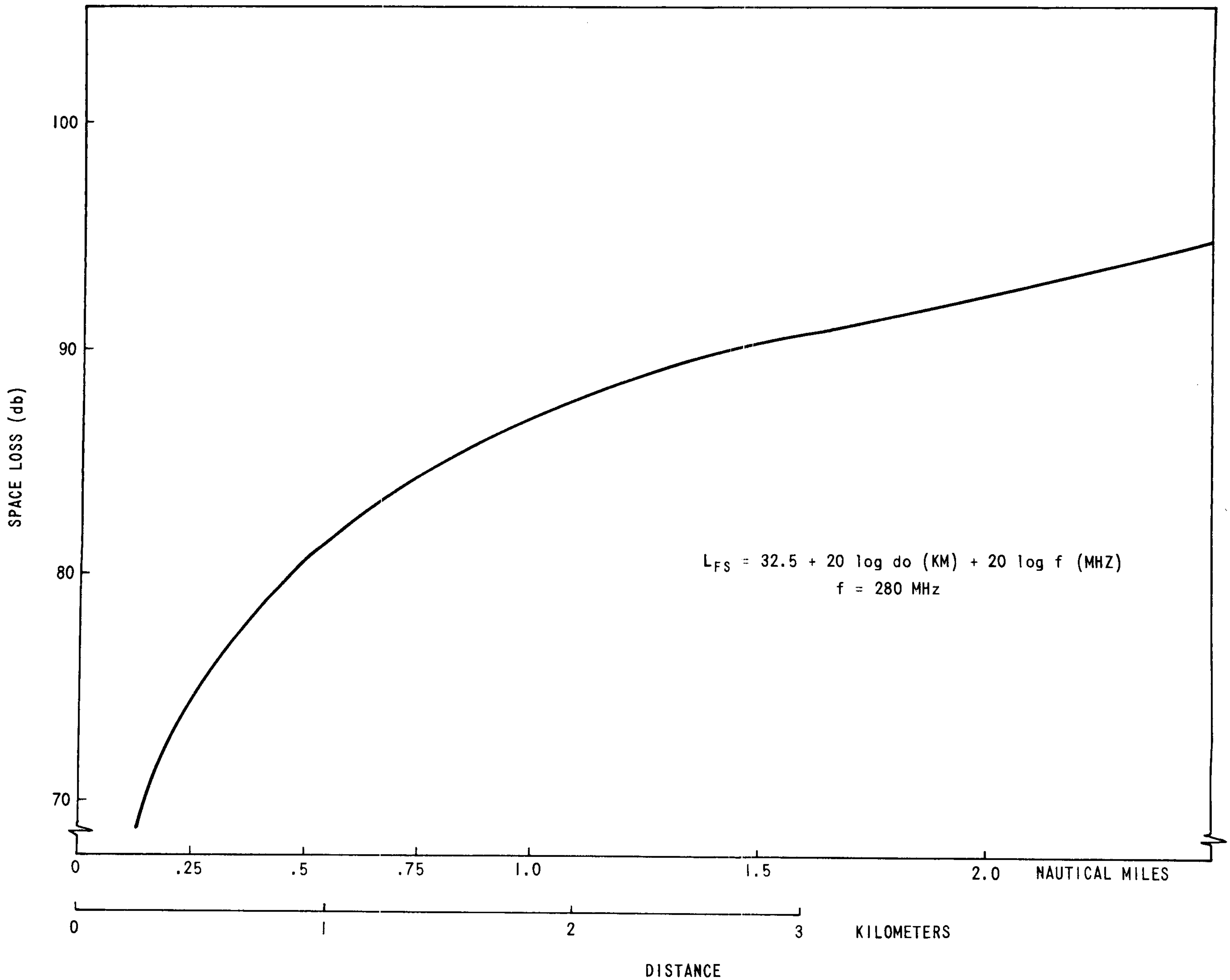


FIGURE 4 - FREE SPACE LOSS vs. DISTANCE

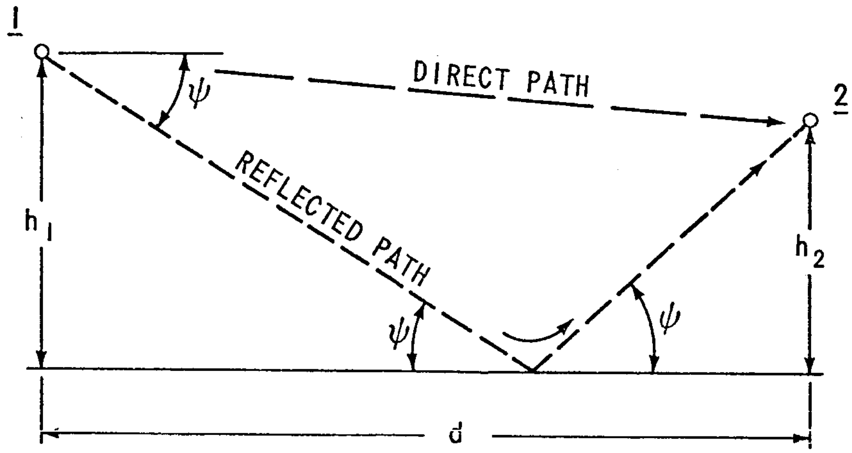
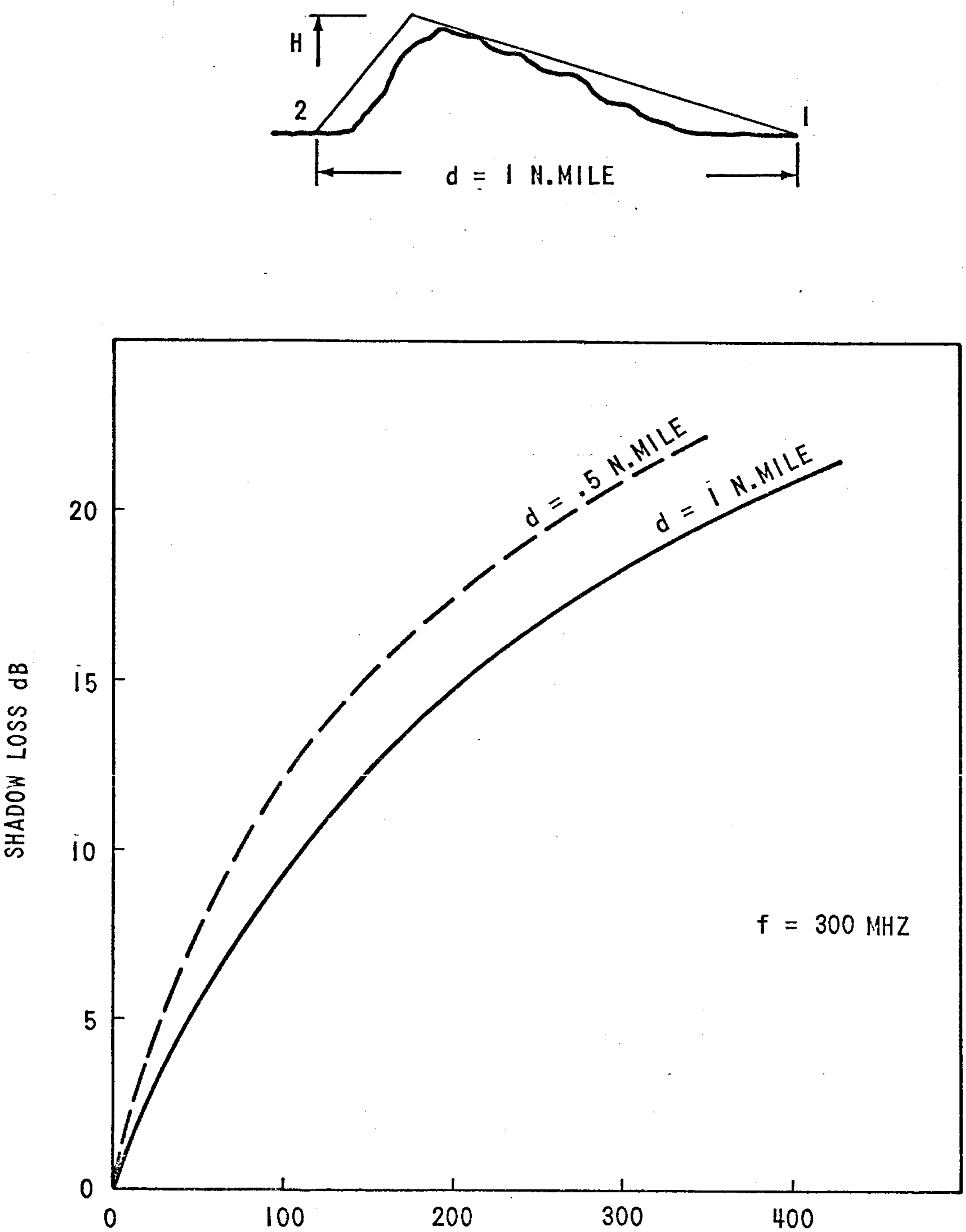


FIGURE 5 - MULTIPATH GEOMETRY

FIGURE 6 ANTENNA HEIGHT GAIN CORRECTION FACTOR
(From ref. 7)



OBSTACLE HEIGHT - FEET

(H FOR 1, .5, N.M. SEPARATION)

(From BTL Data - ref. 7)

FIGURE 7 - SHADOW LOSS vs. OBSTACLE HEIGHT

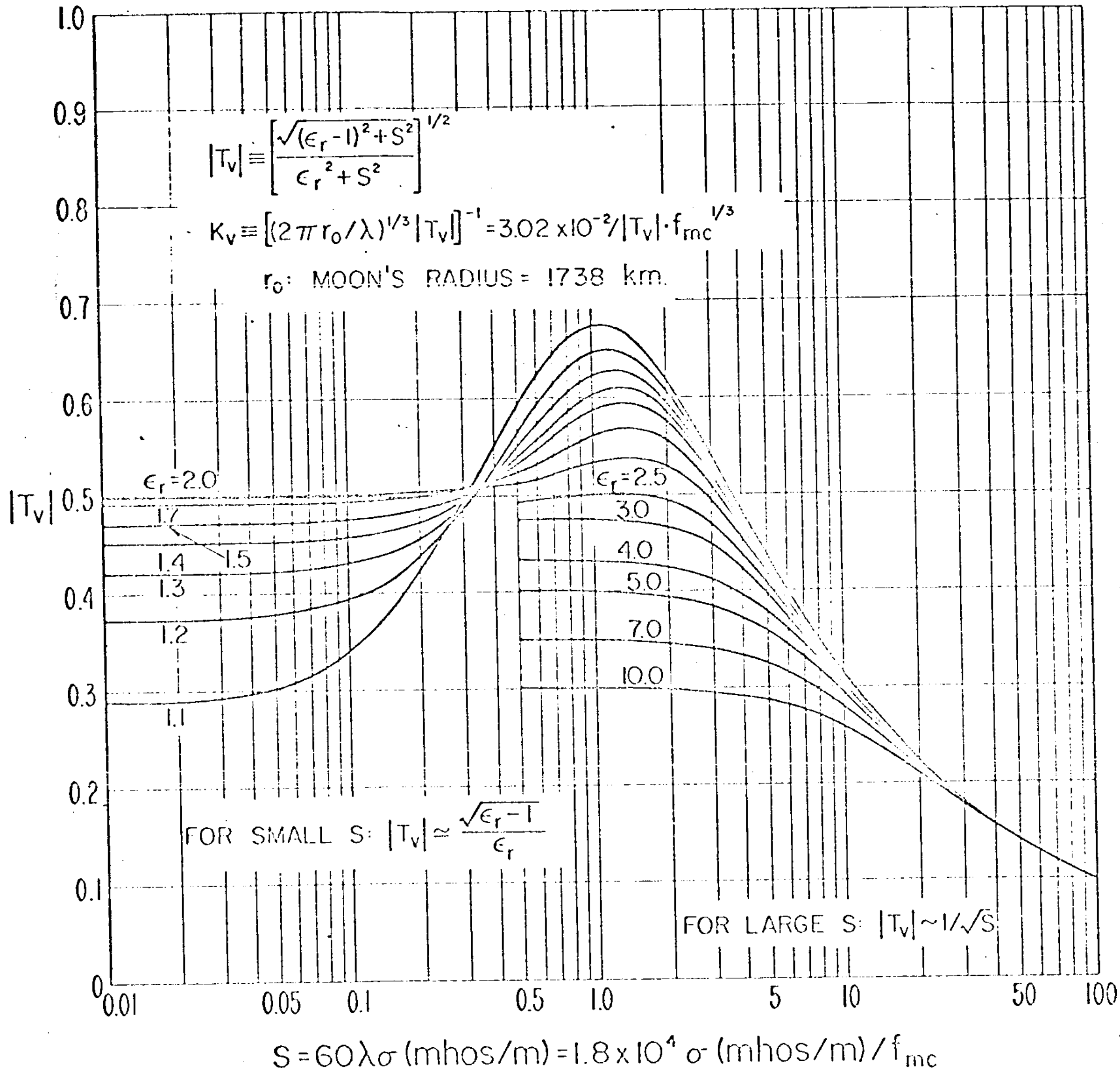


FIGURE 8 The parameter $|T_v|$ for vertical polarization. The formula for K_v assumes a homogeneous ground.

(From Vogler - ref. 4)

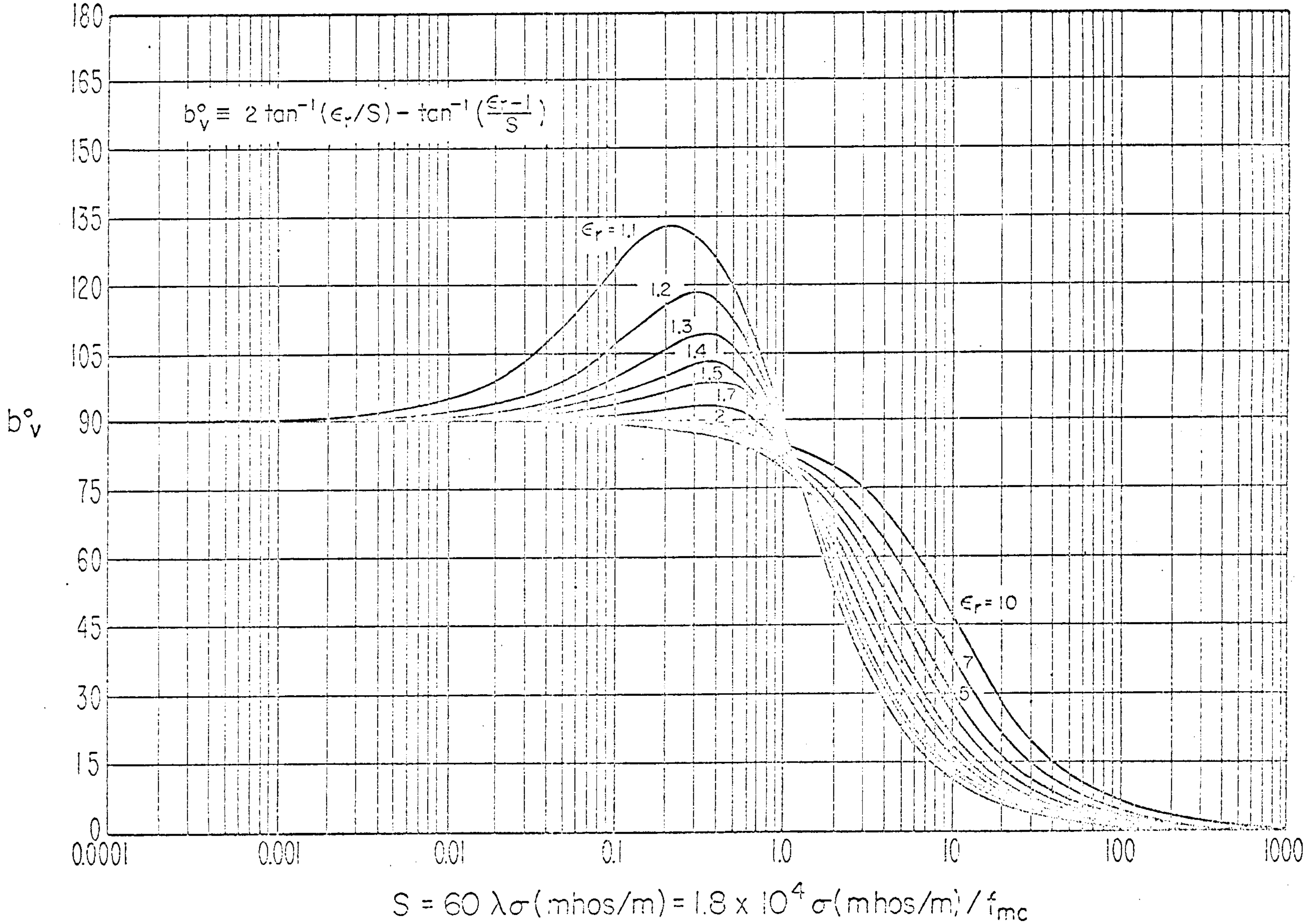


FIGURE 9 The parameter b_v° for vertical polarization and homogeneous ground.
(From Vogler - ref. 4)

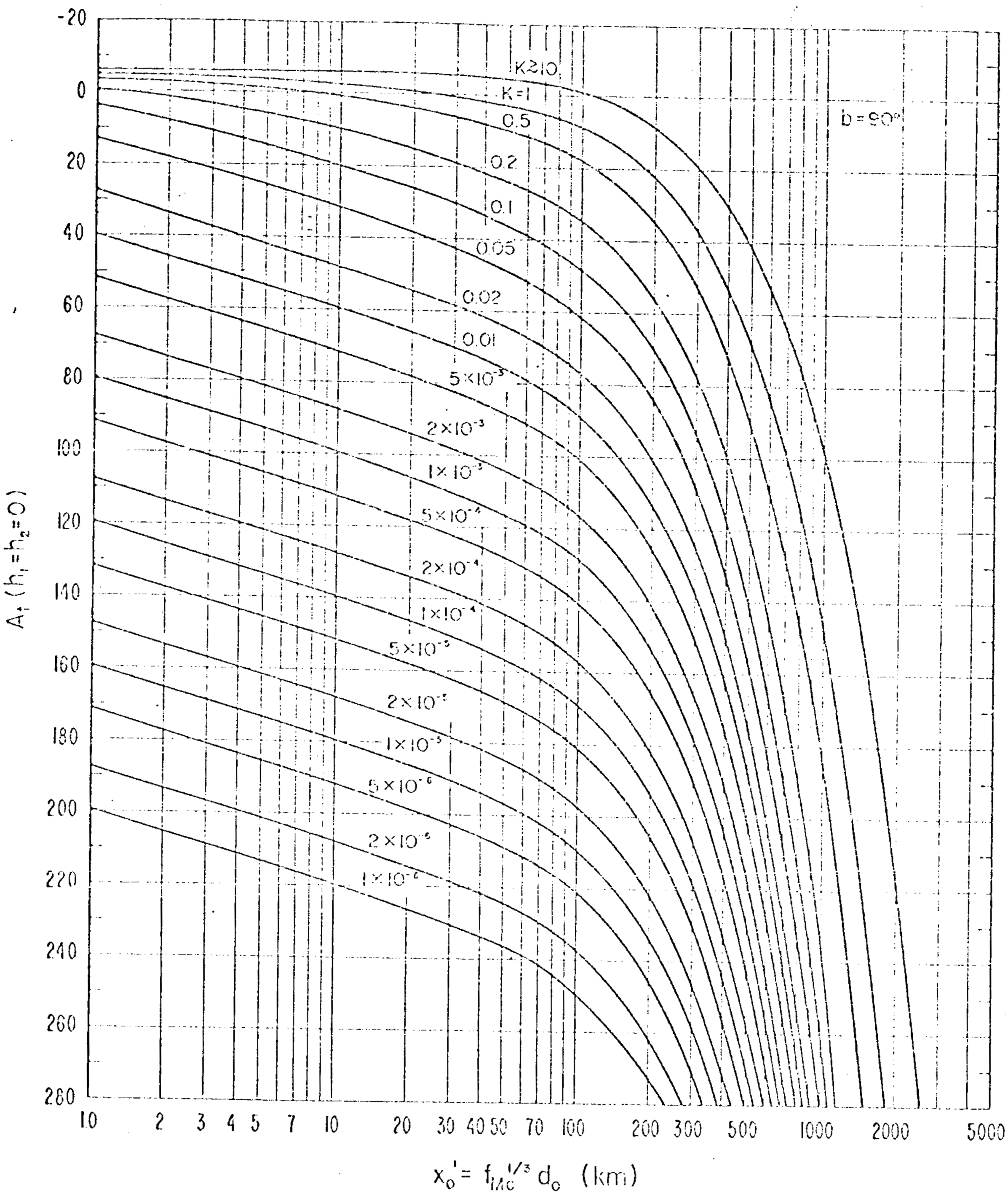


FIGURE 10 Ground wave attenuation for zero antenna heights, $b = 90^\circ$.

(From Vogler - ref. 4)

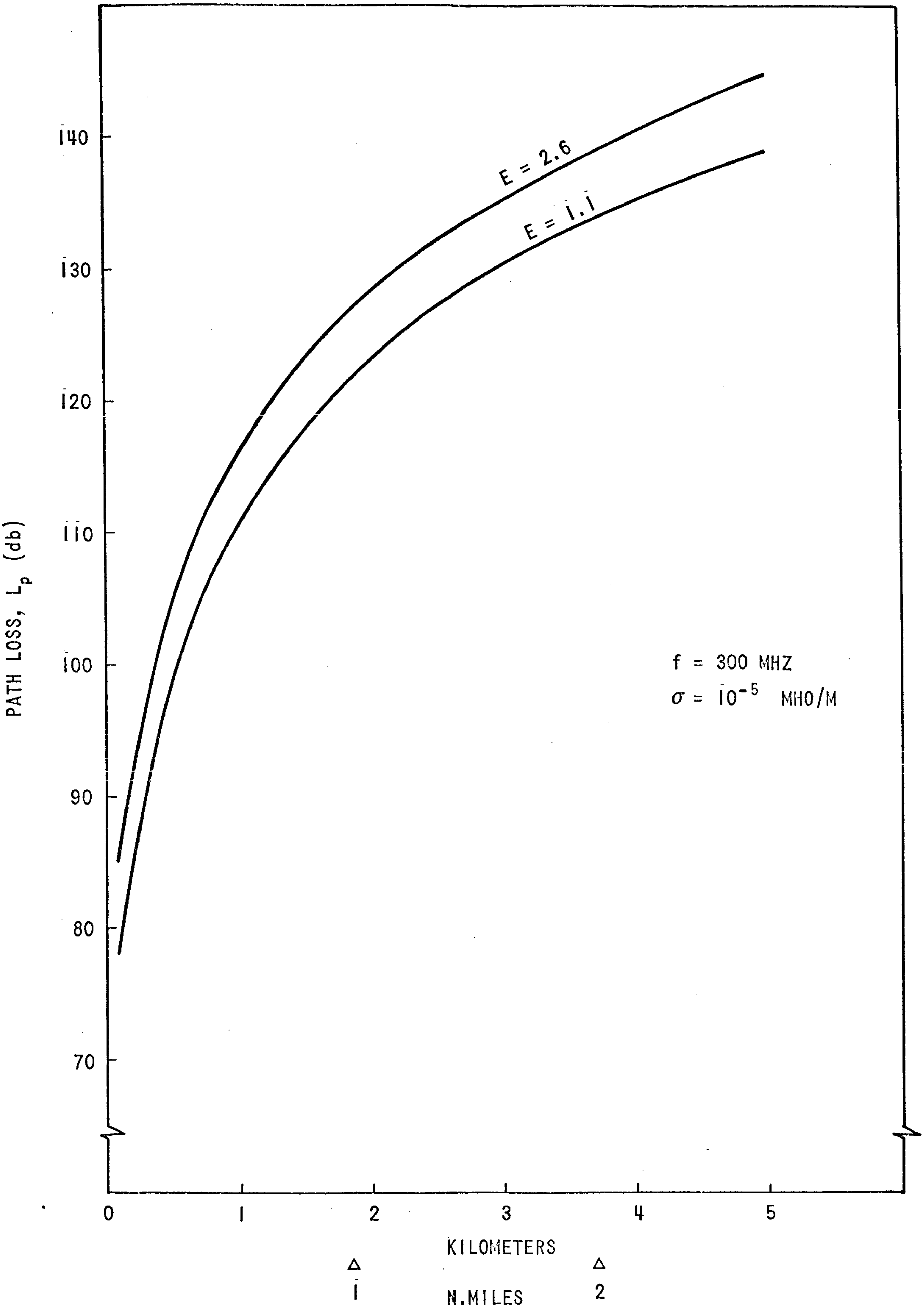


FIGURE 11 - TOTAL PATH LOSS - EVA_1 - EVA_2

BELLCOMM, INC.

Subject: Path Loss Factors in Lunar Surface Communications

From: I. I. Rosenblum

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